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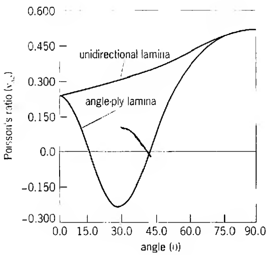

Fig. 5. Through-thickness Poisson's ratios for composite laminate T300/5208.

$\theta = 45°$ where the shear stiffnesses of both the lamina and the laminate are largest, the stiffness of the laminate is more than 3.5 times that of the lamina for the carbon/epoxy under consideration. The results clearly indicate that $\pm 45°$ fiber orientations are desired in structures requiring high shear stiffness. *See* SHEAR.

Coefficients of mutual influence. For anisotropic materials such as fibrous composites, there are additional important engineering properties that describe material behavior. These properties are called coefficients of mutual influence. They are similar to Poisson's ratios in that they provide an indication of the coupling between normal and shear components of strain. This type of coupling is not present in isotropic materials. One of the coefficients of mutual influence for unidirectional off-axis lamina of two different materials (T300/5208 carbon/epoxy and SCS6/Ti-15-3, a metal matrix composite) is the ratio of shear strain to axial strain for applied stress in the axial direction. The most significant features of the results are that the coefficient exhibits vary large gradients and magnitudes for the carbon/epoxy in the vicinity of $\theta = \pm 12°$, and that there is a major difference in maximum values between the two materials. The coefficient of mutual influence can be nearly twice as large as Poisson's ratio. Thus the coupling between axial and shear response can be twice as large as the coupling between axial and transverse response for unidirectional lamina. The effective coefficient of mutual influence is zero for angle-ply laminates because the $+\theta$ and $-\theta$ fiber orientations have the effect of offsetting one another.

Laminate design. A wide variety of effective material properties can be obtained with one type of fibrous composite simply through changes in the stacking arrangement (layer thicknesses and fiber orientations of the individual layers) of the laminate. For example, changing the type of composite provides even more variety in the properties. Thus, material properties of the laminate can be tailored. This is a very important feature of fibrous composites because the material can be designed to have specific material properties.

Coefficient of thermal expansion. The wide variety of coefficients of thermal expansion are possible through changes in the stacking arrangement of a given carbon/epoxy. The coefficient of thermal expansion is the strain associated with a change in temperature of 1°. Most materials have positive coefficients of expansion and thus expand when heated and contract when cooled. The effective axial coefficient of thermal expansion of the carbon/epoxy can be positive, negative, or zero, depending upon the laminate configuration. Laminates with zero coefficient of thermal expansion are particularly important because they do not expand or contract when exposed to a temperature change. Composites with zero (or near zero) coefficient of thermal expansion are therefore good candidates for application in space structures where the temperature change can be 500°F (from −250 to +250°F) [278°C (from −157 to +121°C)] during an orbit in and out of the Sun's proximity. There are many other applications where thermal expansion is a very important consideration.

Carl T. Herakovich

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Composite material

A material system composed of a mixture or combination of two or more macroconstituents that differ in form or material composition and are essentially insoluble in each other. This definition is considered to be too broad by some engineers because it includes many materials that are not usually thought of as composites. For example, in many of the particulate-type composites, such as dispersion-hardened alloys and cermets, the composite structure is microscopic rather than macroscopic. Also, this definition does not draw the line between composite materials and composite structures. However, instead of trying to establish a distinction between materials and structures, it is more useful to make a distinction between mill composites (such as nonmetallic laminates, clad metals, and honeycomb) and specialty composites (such as tires, rocket nose cones, and glass-reinforced plastic boats).

Constituents and Construction

In principle, composites can be constructed of any combination of two or more materials—metallic,

organic, or inorganic; but the constituent forms are more restricted. The matrix is the body constituent, serving to enclose the composite and give it bulk form. Major structural constituents are fibers, particles, laminae or layers, flakes, fillers, and matrices. They determine the internal structure of the composite. Usually, they are the additive phase.

Because the different constituents are intermixed or combined, there is always a contiguous region. It may simply be an interface, that is, the surface forming the common boundary of the constituents. An interface is in some ways analogous to the grain boundaries in monolithic materials. In some cases, however, the contiguous region is a distinct added phase, called an interphase. Examples are the coating on the glass fibers in reinforced plastics and the adhesive that bonds the layers of a laminate together. When such an interphase is present, there are two interfaces, one between the matrix and the interphase and one between the fiber and the interface.

Interfaces are among the most important yet least understood components of a composite material. In particular, there is a lack of understanding of processes occurring at the atomic level of interfaces, and how these processes influence the global material behavior. There is a close relationship between processes that occur on the atomic, microscopic, and macroscopic levels. In fact, knowledge of the sequence of events occurring on these different levels is important in understanding the nature of interfacial phenomena. Interfaces in composites, often considered as surfaces, are in fact zones of compositional, structural, and property gradients, typically varying in width from a single atom layer to micrometers. Characterization of the mechanical properties of interfacial zones is necessary for understanding mechanical behavior.

Nature and performance. Several classification systems for composites have been developed, including classification by (1) basic material combinations, for example, metal-organic or metal-inorganic; (2) bulk-form characteristics, such as matrix systems or laminates; (3) distribution of the constituents, that is, continuous or discontinuous; and (4) function, for example, electrical or structural.

There are five classes under the classification by basic material combinations: (1) fiber composites, composed of fibers with or without a matrix; (2) flake composites, composed of flat flakes with or without a matrix; (3) particulate composites, composed of particles with or without a matrix; (4) filled (or skeletal) composites, composed of a continuous skeletal matrix filled by a second material; and (5) laminar composites, composed of layer or laminar constituents.

There is also a classification based on dimensions. The dimensions of some of the components of composite materials vary widely and overlap the dimensions of the microstructural features of common conventional materials (**Fig. 1**). They range from extremely small particles or fine whiskers to the large aggregate particles or rods in reinforced concrete.

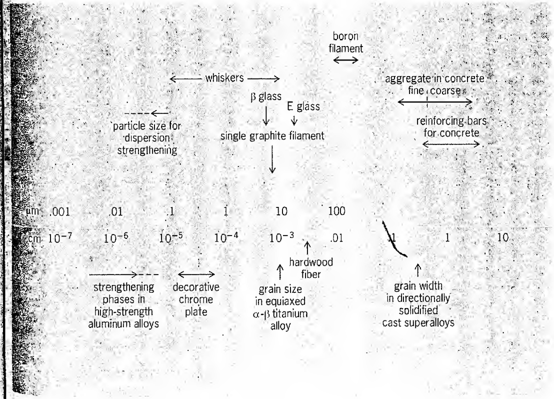

Fig. 1. Dimensional range of microstructural features in composite and conventional materials. Filament and fiber dimensions are diameters. 1 cm = 0.39 in.

See CRYSTAL WHISKERS; REINFORCED CONCRETE.

The behavior and properties of composites are determined by the composition, form and arrangements, and interaction between the constituents. The intrinsic properties of the materials of which the constituents are composed largely determine the general order or range of properties of the composite. Structural and geometrical characteristics—that is, the shape and size of the individual constituents, their structural arrangement and distribution, and the relative amount of each—contribute to overall performance. Of far-reaching importance are the effects produced by the combination and interaction of the constituents. The basic principle is that by using different constituents it is possible to obtain combinations of properties and property values that are different from those of the individual constituents.

A performance index is a property or group of properties that measures the effectiveness of a material in performing a given function. The values of performance indices for a composite differ from those of the constituents.

Fiber-matrix composites. Fiber-matrix composites have two constituents and usually a bonding phase as well.

Fibers. The performance of a fiber-matrix composite depends on orientation, length, shape, and composition of the fibers; mechanical properties of the matrix; and integrity of the bond between fibers and matrix. Of these, orientation of the fibers is perhaps most important.

Fiber orientation determines the mechanical strength of the composite and the direction of greatest strength. Fiber orientation can be one-dimensional, planar (two-dimensional), or three-dimensional. The one-dimensional type has maximum composite strength and modulus in the direction of the fiber axis. The planar type exhibits different strengths in each direction of fiber orientation; and the three-dimensional type is isotropic but has greatly decreased reinforcing values. The mechanical properties in any one direction are proportional to the amount of fiber by volume oriented in that direction. As fiber orientation becomes more random, the mechanical properties in any one direction become lower.

Fiber length also impacts mechanical properties. Fibers in the matrix can be either continuous or short. Composites made from short fibers, if they could be properly oriented, could have substantially greater strengths than those made from continuous fibers. This is particularly true of whiskers, which have uniform high tensile strengths. Both short and long fibers are also called chopped fibers. Fiber length also has a bearing on the processibility of the composite. In general, continuous fibers are easier to handle but have more design limitations than short fibers.

Bonding. Fiber composites are able to withstand higher stresses than their individual constituents because the fibers and matrix interact, resulting in redistribution of the stresses. The ability of constituents to exchange stresses depends on the effectiveness of the coupling or bonding between them. Bonding can sometimes be achieved by direct contact of the two phases, but usually a specially treated fiber must be used to ensure a receptive adherent surface. This requirement has led to the development of fiber finishes, known as coupling agents. Both chemical and mechanical bonding interactions occur for coupling agents.

Voids (air pockets) in the matrix are one cause of failure. A fiber passing through the void is not supported by resin. Under load, the fiber may buckle and transfer stress to the resin, which readily cracks. Another cause of early failure is weak or incomplete bonding. The fiber-matrix bond is often in a state of shear when the material is under load. When this bond is broken, the fiber separates from the matrix and leaves discontinuities that may cause failure. Coupling agents can be used to strengthen these bonds against shear forces. *See* SHEAR.

Reinforced plastics. Probably the greatest potential for lightweight high-strength composites is represented by the inorganic fiber–organic-matrix composites, and no composite of this type has proved as successful as glass-fiber-reinforced plastic composites. As a group, glass-fiber–plastic composites have the advantages of good physical properties, including strength, elasticity, impact resistance, and dimensional stability; high strength-to-weight ratio; good electrical properties; resistance to chemical attack and outdoor weathering; and resistance to moderately high temperatures (about 260°C or 500°F).

A critical factor in reinforced plastics is the strength of the bond between the fiber and the polymer matrix: weak bonding causes fiber pullout and delamination of the structure, particularly under adverse environmental conditions. Bonding can be improved by coatings and the use of coupling agents. Glass fibers, for example, are treated with silane (SiH_4) for improved wetting and bonding between the fiber and the matrix.

Generally, the greatest stiffness and strength in reinforced plastics are obtained when the fibers are aligned in the direction of the tension force. Other properties of the composite, such as creep resistance, thermal and electrical conductivity, and thermal expansion, are anisotropic. The transverse properties of such a unidirectionally reinforced structure are much lower than the longitudinal. Seven mechanical and thermal properties are of direct interest in assessing the potential of a new composite: density, modulus, strength, toughness, thermal conductivity, expansion coefficient, and heat capacity; others, such as fracture toughness and thermal diffusivity, are calculated from them.

Advanced Composites

Advanced composites comprise structural materials that have been developed for high-technology applications, such as airframe structures, for which other

materials are not sufficiently stiff. In these materials, extremely stiff and strong continuous or discontinuous fibers, whiskers, or small particles are dispersed in the matrix. A number of matrix materials are available, including carbon, ceramics, glasses, metals, and polymers. Advanced composites possess enhanced stiffness and lower density compared to fiber-glass and conventional monolithic materials. While composite strength is primarily a function of the reinforcement, the ability of the matrix to support the fibers or particles and to transfer load to the reinforcement is equally important. Also, the matrix frequently dictates service conditions, for example, the upper temperature limit of the composite.

Reinforcements. Continuous filamentary materials that are used as reinforcing constituents in advanced composites are carbonaceous fibers, organic fibers, inorganic fibers, ceramic fibers, and metal wires. Reinforcing inorganic materials are used in the form of discontinuous fibers and whiskers. *See* STRENGTH OF MATERIALS.

Carbon and graphite fibers offer high modulus and the highest strength of all reinforcing fibers. These fibers are produced in a pyrolysis chamber from three different precursor materials—rayon, polyacrylonitrile (PAN), and pitch. High-modulus carbon fibers are available in an array of yarns and bundles of continuous filaments (tows) with differing moduli, strengths, cross-sectional areas, twists, and plies. *See* CARBON; GRAPHITE.

Almost any polymer fiber can be used in a composite structure, but the first one with high-enough tensile modulus and strength to be used as a reinforcement in advanced composites was an aramid, or aromatic polyamide, fiber. Aramid fibers have been the predominant organic reinforcing fiber; graphite is a close second. *See* MANUFACTURED FIBER; POLYMER.

The most important inorganic continuous fibers for reinforcement of advanced composites are boron and silicon carbide, both of which exhibit high stiffness, high strength, and low density. Continuous fibers are made by chemical vapor deposition processes. Other inorganic compounds that provide stiff, strong discontinuous fibers that predominate as reinforcements for metal matrix composites are silicon carbide, aluminum oxide, graphite, silicon nitride, titanium carbide, and carbon carbide. *See* BORON.

Polycrystalline aluminum oxide (Al_2O_3) is a commercial continuous fiber that exhibits high stiffness, high strength, high melting point, and exceptional resistance to corrosive environments. One method to produce the fibers is dry spinning followed by heat treatment.

Whiskers are single crystals that exhibit fibrous characteristics. Compared to continuous or discontinuous polycrystalline fibers, they exhibit exceptionally high strength and stiffness. Silicon carbide whiskers are prepared by chemical processes or by pyrolysis of rice hulls. Whiskers made of aluminum oxide and silicon nitride are also available. Particulates vary widely in size, characteristics, and function; and since particulate composites are usually isotropic, their distribution is usually random rather than controlled. *See* PYROLYSIS.

Organic-matrix composites. In many advanced composites the matrix is organic, but metal matrices are also used. Organic matrix material are lighter than metals, adhere better to the fibers, and offer more flexibility in shaping and forming. Ceramic matrix composites, carbon-carbon composites, and intermetallic matrix composites have applications where organic or metal matrix systems are unsuitable.

Materials. Epoxy resins have been used extensively as the matrix material. However, bismaleimide resins and polyimide resins have been developed to enhance in-service temperatures. Thermoplastic resins, polyetherketone, and polyphenylene sulfide are in limited use.

The continuous reinforcing fibers for organic matrices are available in the forms of monofilaments, multifilament fiber bundles, unidirectional ribbons, roving (slightly twisted fiber), and single-layer and multilayer fabric mats. Frequently, the continuous reinforcing fibers and matrix resins are combined into a nonfinal form known as a prepreg.

Fabrication. Many processes are available for the fabrication of organic matrix composites. The first process is contact molding in order to orient the unidirectional layers at discrete angles to one another. Contact molding is a wet method, in which the reinforcement is impregnated with the resin at the time of molding. The simplest method is hand lay-up, whereby the materials are placed and formed in the mold by hand and the squeezing action expels any trapped air and compacts the part.

Molding may also be done by spraying, but these processes are relatively slow and labor costs are high, even though they can be automated. Many types of boats, as well as buckets for power-line servicing equipment, are made by this process.

Another process is vacuum-bag molding, where prepregs are laid in mold to form the desired shape. In this case, the pressure required to form the shape and achieve good bonding is obtained by covering the lay-up with a plastic bag and creating a vacuum. If additional heat and pressure are desired, the entire assembly is put into an autoclave. In order to prevent the resin from sticking to the vacuum bag and to facilitate removal of excess resin, various materials are placed on top of the prepreg sheets. The molds can be made of metal, usually aluminum, but more often are made from the same resin (with reinforcement) as the material to be cured. This eliminates any problem with differential thermal expansion between the mold and the part.

In filament winding, the resin and fibers are combined at the time of curing. Axisymmetric parts, such as pipes and storage tanks, are produced on a rotating mandrel. The reinforcing filament, tape, or roving is wrapped continuously round the form. The reinforcements are impregnated by passing them

through a polymer bath. However, the process can be modified by wrapping the mandrel with prepreg material. The products made by filament winding are very strong because of their highly reinforced structure. For example, filament winding can be used directly over solid-rocket-propellant forms.

Pultrusion is a process used to produce long shapes with constant profiles, such as rods or tubing, similar to extruded metal products. Individual fibers are often combined into a tow, yarns, or roving, which consists of a number of tows or yarns collected into a parallel bundle without twisting (or only slightly so). Filaments can also be arranged in a parallel array called a tape and held together by a binder. Yarns or tows are often processed further by weaving, braiding, and knitting or by forming them into a sheetlike mat consisting of randomly oriented chopped fibers or swirled continuous fibers held together by a binder.

Weaving to produce a fabric is a very effective means of introducing fibers into a composite. There are five commonly used patterns (**Fig. 2**). Although weaving is usually thought of as a two-dimensional process, three-dimensional weaving is often employed.

Knitting is a process of interlooping chains of tow or yarn. Advantages of this process are that the tow or yarn is not crimped as happens in weaving, and higher mechanical properties are often observed in the reinforced product. Also, knitted fabrics are easy to handle and can be cut without falling apart.

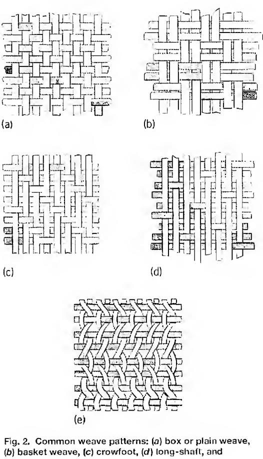

Fig. 2. Common weave patterns: (*a*) box or plain weave, (*b*) basket weave, (*c*) crowfoot, (*d*) long-shaft, and (*e*) leno weave.

In braiding, layers of helically wound yarn or tow are interlaced in a cylindrical shape, and interlocks can be produced at every intersection of fibers. During the process, a mandrel is fed through the center of a braiding machine at a uniform rate, and the yarn or tow from carriers is braided around the mandrel at a controlled angle. The machine operates like a maypole, the carriers working in pairs to accomplish the over-and-under sequencing. The braiding process is most effective for cylindrical geometries. It is used for missile heat shields, lightweight ducts, fluid-sealing components such as packings and sleevings, and tubes for insulation.

Carbon-carbon composites. A carbon-carbon composite is a specialized material made by reinforcing a carbon matrix with continuous carbon fiber. This type of composite has outstanding properties over a wide range of temperatures in both vacuum and inert atmospheres. It will even perform well at elevated temperatures in an oxidizing environment for short times. It has high strength, modulus, and toughness up to 2000°C (3600°F); high thermal conductivity; and a low coefficient of thermal expansion. A material with such properties is excellent for rocket motor nozzles and exit cones, which require high-temperature strength as well as resistance to thermal shock. Carbon-carbon composites are also used for aircraft and other high-performance brake applications that take advantage of the fact that carbon-carbon composites have the highest energy-absorption capability of any known material. If a carbon-carbon composite is exposed to an oxygen-containing atmosphere above 600°C (1100°F) for an appreciable time, it oxidizes, and therefore it must be protected by coatings.

Metal-matrix composites. Metal-matrix composites are usually made with alloys of aluminum, magnesium, or titanium; and the reinforcement is typically a ceramic in the form of particulates, platelets, whiskers, or fibers, although other systems may be used. Metal-matrix composites are often classified as discontinuous or continuous, depending on the geometry of the reinforcement. Particulates, platelets, and whiskers are in the discontinuous category while the continuous category is reserved for fibers and wires. The type of reinforcement is important in the selection of a metal-matrix composite, because it determines virtually every aspect of the product, including mechanical properties, cost, and processing method. The primary methods for processing of discontinuous metal-matrix composites are powder metallurgy, liquid metal infiltration, squeeze or pressure casting, and conventional casting; however, most of these methods do not result in finished parts. Therefore, most discontinuously reinforced metal-matrix composites require secondary processing, which includes conventional wrought metallurgy operations such as extrusion, forging, and rolling; and standard and nonstandard machining operations; and joining techniques such as welding and brazing.

See BRAZING; MACHINING; METAL CASTING; POWDER METALLURGY; WELDING AND CUTTING OF METALS.

Mel M. Schwartz

Ceramic-matrix composites. In general, ceramics are brittle engineering materials with limited reliability. Brittleness is connected with the structure and chemical bonding of the main constituents, and reliability is connected with the stochastic character of main phases and defect distribution within the polycrystalline ceramic body. In spite of the generally high strength, hardness, and chemical and shape stability of ceramics, these two negative properties disqualify their wider application in industry. Ceramic-matrix composites are designed as materials with higher fracture resistance (less brittleness), higher reliability, and in particular cases higher strength compared to monolithic ceramics. These attributes are required for high technologies, especially in the aircraft, automotive, engineering, and energy industries. *See* BRITTLENESS; CERAMICS.

Ceramic composites are materials with at least two constituents, the ceramic-matrix phase and reinforcing-toughening filaments. The filaments cover a wide range of dimensions, from nanoinclusions, through micro-whiskers, to fibers that are several centimeters to a few meters long.

Ceramic nanocomposites. These composites have at least one of the main constituents at the nanometer scale (from one to several hundred nanometers). Typical examples of such ceramic nanocomposites are silicon carbide–silicon nitride (SiC/Si_3N_4) and silicon carbide–alumina (SiC/Al_2O_3). Benefits from the design of these materials are better mechanical properties at room temperature or high temperature, as well as improved electric and magnetic properties. *See* NANOSTRUCTURE.

Examples of some properties of nanocomposites are as follows: A SiC/Si_3N_4 nanocomposite containing 20 vol % SiC has a bending strength greater than 1 GPa (10000 atm) up to 1400°C (2552°F), and a fracture toughness of 7 $MPa{\cdot}m^{1/2}$. Silver–ferrite oxide nanocomposite (Ag/Fe_2O_3) exhibits a superparamagnetic state at temperatures greater than 100 K (−173°C; −280°F).

Based on distribution of nanograins within the matrix, ceramic nanocomposites can be formally divided into intra type, inter type, intra/inter type, and nano/nano type. The SiC/Si_3N_4 nanocomposite (Fig. 3) can be considered an intra/inter type, because of distribution of SiC grains at grain boundaries as well as within the Si_3N_4 grains.

Whisker/platelet-reinforced composites. This ceramic composite contains whiskers or platelets. The whiskers are randomly distributed within the composite matrix. Silicon carbide or silicon nitride whiskers are usually embedded in a silicon carbide, silicon nitride, or alumina matrix. Improvement of the mechanical properties of these composites is reached by dissipation of the crack tip energy on a whisker or platelet. Whisker length varies between several micrometers and hundreds of micrometers. A typical parameter that determines a whisker shape is the aspect ratio, or the length-to-thickness ratio. Platelets are single crystals of flake shape. Their aspect ratio is the diameter-to-thickness ratio. Despite lower effectivity of platelets in dissipating crack tip energy compared to the whiskers, their application is forced due to the environmental unacceptability of whiskers. The bending strength of Si_3N_4/Si_3N_4 ceramics is 0.8–1 GPa (8000–10,000 atm), and fracture toughness is 6 $MPa{\cdot}m^{1/2}$ at room temperature.

Ceramic fiber-matrix composites. In principle, these composites are similar to fiber-matrix composites. The difference is in the composition of fibers, the matrices, and the processing routes.

The typical examples of fibers are the silicon carbide or alumina fibers. Fibers are polycrystalline materials with high tensile strength. Silicon carbide fiber tensile strength for Hi-Nicalon-S fiber is greater than 3 GPa (30,000 atm).

Silicon carbide, silicon nitride, and alumina ceramics are typically used as the matrices. Carbon as a constituent of these composites is also used either in the form of fibers or as a matrix.

There are several processes of embedding the continuous fibers into the ceramic matrix: polymer impregnation and pyrolysis, slurry impregnation and hot pressing, and chemical vapor infiltration.

These materials exhibit a high tensile strength when the fibers are oriented in the direction of the tensile force, and a very high work of fracture, which means a high fracture toughness. For example, the tensile strength of a SiC/Si_3N_4 composite is 0.5 GPa (5000 atm), and the fracture toughness is 26.5 $MPa{\cdot}m^{1/2}$.

Laminate/layered ceramic composites. These ceramic composites consist of two or more different ceramic sheets which are repeated several times through the ceramic body. These materials are usually produced by tape casting in order to built the ceramic "green" body, which is densified by hot pressing or gas pressure sintering. The properties of this type of ceramics are highly anisotropic in different directions.

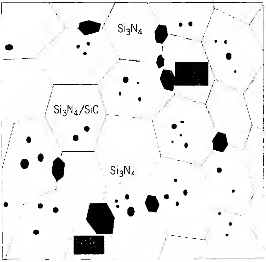

Fig. 3. Schematic of a SiC/Si_3N_4 nanocomposite. This microstructure consists of silicon carbide inclusions within silicon nitride grains, and silicon carbide grains located at the grain boundaries.

parallel and perpendicular to the layer area. The layers can differ by composition or by microstructure. Mechanical properties of silicon nitride-based layered composite are in particular cases exceptional: for example, a bending strength of 1.2 GPa (12,000 atm) and a fracture toughness of 10 MPa·m$^{1/2}$ are reported. *See* SINTERING.

Layered materials offer a possibility to design materials with multifunctions, exhibiting excellent mechanical properties and improved electrical, thermal, or magnetic properties. Pavol Šajgalík

Applications

The use of fiber-reinforced materials in engineering applications has grown rapidly. Selection of composites rather than monolithic materials is dictated by the choice of properties. The high values of specific stiffness and specific strength may be the determining factor, but in some applications wear resistance or strength retention at elevated temperatures is more important. A composite must be selected by more than one criterion, although one may dominate.

Components fabricated from advanced organic-matrix-fiber-reinforced composites are used extensively on commercial aircraft as well as for military transports, fighters, and bombers. The propulsion system, which includes engines and fuel, makes up a significant fraction of aircraft weight (frequently 50%) and must provide a good thrust-to-weight ratio and efficient fuel consumption. The primary means of improving engine efficiency are to take advantage of the high specific stiffness and strength of composites for weight reduction, especially in rotating components, where material density directly affects both stress levels and critical dynamic characteristics, such as natural frequency and flutter speed.

Composites consisting of resin matrices reinforced with discontinuous glass fibers and continuous-glass-fiber mats are widely used in truck and automobile components bearing light loads, such as interior and exterior panels, pistons for diesel engines, drive shafts, rotors, brakes, leaf springs, wheels, and clutch plates.

The excellent electrical insulation, formability, and low cost of glass-fiber-reinforced plastics have led to their widespread use in electrical and electronic applications ranging from motors and generators to antennas and printed circuit boards.

Composites are also used for leisure and sporting products such as the frames of rackets, fishing rods, skis, golf club shafts, archery bows and arrows, sailboats, racing cars, and bicycles.

Advanced composites are used in a variety of other applications, including cutting tools for machining of superalloys and cast iron and laser mirrors for outer-space applications. They have made it possible to mimic the properties of human bone, leading to development of biocompatible prostheses for bone replacements and joint implants. In engineering, composites are used as replacements for fiber-reinforced cements and cables for suspension bridges. *See* MATERIALS SCIENCE AND ENGINEERING. Mel M. Schwartz

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Composition board

A wood product in which the grain structure of the original wood is drastically altered. Composition board may be divided into several types. When wood serves as the raw material for chemical processing, the resultant product may be insulation board, hardboard, or other pulp product. When the wood is broken down only by mechanical means, the resultant product is particle board. Because composition board can use waste products of established wood industries and because there is a need to find marketable uses for young trees, manufacture of composition board is one of the most rapidly developing portions of the wood industry. *See* PAPER.

Fiberboard. One form of fiberboard is produced by loading a batch of wood chips into a chamber which is then heated and pressurized by steam. After about 2 min, the 1000-lb/in.^{2} (6.9-megapascal) pressure is abruptly released to hydrolyze and fluff the chips into a brown fiber. The fiber is refined, washed, and felted into a mat on a wire conveyor so that some of the water can drain out, and then the mat is cut to length for loading on a screen into a press. At controlled temperature in the press, the lignin rebonds the material while water is driven off as steam through the screen. The finished reconstituted wood product is a hard isotropic board as a consequence of the felting of the fibers and the ligneous bonding, possibly augmented by synthetic adhesive.

Alternatively, a similar board is produced by a continuous process. A screw feed delivers wood chips from a hopper to a steam preheater where the chips partially hydrolyze in the vicinity of 150 lb/in.^{2} (0.11 MPa). The hot chips pass between grinding disks to discharge as pulp, which is then formed into sheets essentially as described above. The wood chips may also be processed entirely by grinding. A further variation is to deliver the pulp slurry into a deckle box, in which case most of the water is removed by suction applied below the box before the mat is compressed into the finished sheet.